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Environmental Planning and Uncertainty

Risø-R-709(EN)

Lene Sørensen

Risø National Laboratory, Roskilde, Denmark
January 1994

Abstract In recent years, environmental planning has become an important public, social task for regulation and control of serious environmental problems. There has been a tendency on the scientific side of the planning process to use mathematical models in analyses, etc. In some cases mathematical models have been used directly in the political decision-making process.

This thesis has focused on analyzing the environmental planning process, the application of scientific information in the form of mathematical models, as well as the identification of significant factors that can give rise to uncertainty and affect the structure and outcome of the process.

Three concrete examples of environmental planning are presented and analyzed: the Danish Water Action Plan, the Dutch National Environmental Policy Plan, and the planning process for regulation of acidifying emissions in Europe.

The three cases represent different examples of how planning and decision-making can be carried out, and how mathematical models and their results can be used. The thesis has illustrated this and concluded that mathematical models can be used for different purposes, and that they can be made to play a central role in the planning. The planning examples show that models (or their results) can be employed in at least three different ways; in a justifying role for specific political decisions; in a supporting role for decision-making; and in a more steering role where the planning is virtually determined with respect to the perception of the problem and possible solutions. Furthermore, the limitations on the use of models in planning processes are discussed.

Uncertainty has been identified in the case studies as a central factor in planning, — in the technical/scientific part as well as in the political part. Three types of uncertainty in environmental planning are identified: technical uncertainty; structural uncertainty; socio-political uncertainty. Several sources of uncertainty were identified in the technical/scientific part of planning as well as in the political/decision-making part, and the different types of uncertainty were classified. Methods of coping with the technical uncertainty aspects are subject to many limitations when used on existing types of models. Other types of uncertainty can hardly be handled at all. The thesis therefore suggests a widening of the concept of model evaluation in order to cope with the model uncertainty elements identified, and to assess applicability of the models in planning and decision-making. One conclusion of the thesis is, that if one wants to cope with influential uncertainty elements, it will be necessary to make more socially related analyses directed at the ways in which society deals with environmental problems.

The present report represents one part of the Ph.D. dissertation "Environmental Planning and Uncertainty" submitted to the Technical University of Denmark, Lyngby, Denmark. The defence took place the 17 November 1993.

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Abstract (in Danish) Miljøplanlægning er i de senere år blevet en vigtig samfundsopgave til regulering og kontrol af alvorlige miljøproblemer. Indenfor de videnskaber, der deltager i miljøplanlægningen, er der en tendens til at anvende matematiske modeller i analyser osv. Nogen gange forsøger man at anvende modeller direkte i den politiske beslutningsproces.

Denne afhandling har fokuseret på at analysere miljøplanlægningsprocessen og dens brug af videnskabelig information i form af matematiske modeller, samt at identificere faktorer i processen, der kan være årsag til usikkerhed og influere på processens struktur og resultat.

Tre konkrete eksempler på miljøplanlægning er præsenteret og analyseret i to case studier. Det er de processer, der førte til den danske Vandmiljøplan og den hollandske Nationale Miljøplan, samt planlægningsprocessen bag den internationale protokol til regulering af forsurende emissioner.

De tre eksempler er forskellige varianter af, hvorledes planlægning og beslutningstagen kan foregå og på anvendelse af matematiske modeller og deres resultater. Afhandlingen har illustreret og konkluderet, at matematiske modeller kan anvendes med forskelligt formål, og spille en central rolle i planlægningen. Planlægningseksemplerne viser, at modellerne (eller resultater fra modelkørsler) kan anvendes på mindst tre forskellige måder: I en retfærdiggørende rolle for politiske beslutninger, i en støttende rolle for beslutningstagen, samt i en mere styrende rolle, hvor modellerne nærmest styrer planlægningen mht. synet på problemet og de mulige løsninger. Begrænsningerne for anvendelse af modeller i planlægningsprocessen er ligeledes diskuteret.

Usikkerhed er udfra case studierne blevet identificeret som en central faktor i planlægningen - såvel den teknisk/videnskabelige del som den politiske del. Afhandlingen har identificeret tre typer af usikkerhed, som eksisterer i miljøplanlægning: Teknisk usikkerhed, strukturel usikkerhed samt samfunds-politisk usikkerhed. Der er identificeret adskillige kilder (elementer) såvel i den teknisk/videnskabelige del af planlægningen som i den politiske/beslutnings-tagende del. Usikkerhedselementerne er klassificeret i en form for usikkerhedstaxonomi. De metoder, man har til håndtering af teknisk usikkerhed, har store begrænsninger, hvis de anvendes i eksisterende modeller. Andre typer af usikkerhed kan ofte slet ikke håndteres. Der er derfor blevet foreslået at udvide modelevalueringsbegrebet, således at de mere model relaterede usikkerheds-elementer og hele modellen som sådan kan vurderes i forhold til deres anvendelse. Det er konklusionen af studiet, at for at håndtere alle usikkerhedselementer i en planlægningsprocess må der udføres mere samfundsorienterede analyser, som rettes mod hele samfundets måde at løse miljøproblemer på.

Nærværende rapport repræsenterer en del af Ph.D. afhandlingen "Miljø-planlægning og Usikkerhed" som er blevet udført ved Danmarks Tekniske Højskole, Lyngby, Danmark. Forsvaret foregik den 17. november 1993.

Contents

Preface

This report together with parts 2 and 3 marks the end of my Ph.D. study. The reports represent my Ph.D. thesis, of which the present report shall be seen as the core in which the more general findings and conclusions from parts 2 and 3 are summarized and discussed. It has been a challenge and of great interest to study the broad area of environmental planning as it is carried out in real life and to study the application and use of mathematical models in practical planning. For me as an engineer, it was natural to focus on the more technical and methodological aspects of the planning process. It became clear that uncertainty is a key issue affecting many different fields of science: the technical, physical, sociological, and more policy oriented sciences, to mention a few. Therefore, a large part of my studies has been devoted to analysing aspects of uncertainty associated with environmental planning.

The work has mainly been carried out at the Systems Analysis Department, Risø National Laboratory, Roskilde, in collaboration with the Institute for Mathematical Statistics and Operations Research (IMSOR), the Technical University of Denmark, Lyngby. As part of the requirements for the Ph.D. degree, nine months was spent at the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. The diversity in work, and differences between the institutions have been valuable and highly inspiring for the studies.

Several people have been sources of inspiration and have provided stimulating comments. I shall specifically express my gratitude to my supervisors Dr. Victor Vidal, Gordon Mackenzie, Ph.D and Hans Ravn, Ph.D. who have guided me through the whole process. I am, however, particularly grateful to Dr. Victor Vidal for his support and involvement. It would have been difficult to manage without his inspiration, constructive ideas, criticism, and teasing remarks. I am also indebted to Markus Amann, Ph.D. for providing a helpful and warm atmosphere during my studies at IIASA.

The Danish Research Academy and Risø National Laboratory have provided financial support for the studies and the stay in Austria. Risø National Laboratory has also provided me with the necessary facilities and time to finish the studies. For this I am deeply grateful.

Finally, my best thanks go to Søren who has given me invaluable support and encouragement, and has helped out with the graphics.

Roskilde, January 1994

Lene Sørensen

1 Introduction

Within the constitutional framework of national legislation, scientific findings are commonly used to support political decisions. Research and political decision-making are considered equally indispensable factors in the task of providing solutions to problems of society. Behind this ideology lies the assumption that political arguments are strengthened when they are supported by scientific arguments. Hence the roles of the actors concerned with and participating in *the decision-making process* are clear: researchers are expected to find the scientific and technical information required and to present it objectively and with a high degree of certainty, while decision-makers have to decide on the goals and means of solving social problems, making use of the scientific facts in their political considerations. This is also the traditional, ideological framework of environmental planning and decision-making.

Over the last century environmental problems have received a high degree of attention and recognition. The scope of the problems has expanded considerably from being of purely local interest (in relation to pollution and polluters) to becoming of national, regional, and global concern. Management of environmental problems, i.e., regulation and control, has become a task involving issues of natural science, physics, economics, and technology which must be taken into account simultaneously. This puts high demands on researchers analyzing individual issues and their relationships. At the same time, it is evident that environmental problems are becoming high priority issues in society and are putting pressure on decision-makers to take action through rational and efficient decisions based on scientific findings. It is therefore of relevance to focus attention on how the scientific findings are presented and utilized.

Mathematical models play a central role in the context of today's scientific findings. The models (here and in the following models refer to mathematical models) provide a framework for analyzing possible relationships in society and for giving a holistic overview over causes and effects of for example pollution problems. Through use in research activities, models become a communication tool between scientists and decision-makers. The development and application of *Integrated Environmental Models* is one attempt to provide a mathematical tool for overall analyses of environmental problems where aspects of several scientific disciplines and their relationships are described. This type of model is one example of tools designed to support or being used directly in the environmental planning process.

Environmental problems cannot be fully described and explained by scientific means. There are still many gaps in our knowledge, and mathematical models can only become approximations of real world processes and systems. With the extention of environmental problems, both in scale and number of issues involved, the number of actors taking part in the planning has grown. The actors may be various scientists viewing the issues differently, non-governmental organizations, and decision-makers from all levels of society. Environmental planning and decision-making thereby become more complex, including more potential conflicts and uncertainty.

The uncertainty concept shall be understood here in broad terms as lack of knowledge about the value of a quantity obtained from a model, - for instance concerning the relationship between different factors describing a large system of some kind, or about the outcome of making a specific decision (the uncertainty concept is considered in more detail in Chapter 3). Uncertainty is an inherent part of scientific research and analysis as well as of the decision-making process. Because they are difficult to handle, the uncertainties of problem-solving are often disregarded or inadequately dealt with. In any case, uncertainty and the way it is handled can have a major influence not only on the decisions reached, but also on the way the planning and decision-making process evolves.

Given the framework of traditional problem-solving, the thesis has two overall **purposes**:

a. to analyze the use and role of mathematical models in environmental planning and decision-making, and to discuss the limitations of models in such practical real life activities. Integrated Environmental Models are considered as representives of models used in planning activities.

b. to analyze the decision-making process in terms of uncertainty factors (i.e. types of uncertainty and sources from which they arise) influencing the process, and to discuss limitations on how these points are handled in practice.

The work was based on the following **hypotheses**:

- That mathematical models, when used in real world planning and decision-making, have a certain role that does not necessarily follow the traditions of environmental planning and decision-making.
- That there exists a large number of uncertain factors (types or sources from which uncertainty arise) on both the scientific and the decision-making side of environmental planning and that these are managed only to a limited extent.
- That existing methods (approaches) of handling uncertainty are not easily applicable to Integrated Environmental Models and the decision-making process as a whole.

In practice the research was carried out by first analyzing three concrete examples of environmental planning and decision-making. These are presented in two case studies.

Two examples of national environmental decision-making processes are presented in *the first case study*. Both processes resulted in formulation and adoption of plans: The Danish Water Action Plan (adopted in January, 1987), and the Dutch National Environmental Policy Plan (adopted in June, 1990). These examples were seen as representative of national planning processes. Both processes encountered much criticism and many obstacles before adoption, and can be seen as different variations of the traditions of planning and decision-making. Mathematical models were used differently and with different success in the processes, which thus present a basis for discussions about the roles of mathematical models in such processes. The examples are used to identify different uncertainty types and elements influencing the process, and as a basis for suggesting an alternative way of conducting planning and decision-making where explicit consideration is given to the management of uncertainties. The case study is described in part two of the thesis and is named "Environmental Planning and Decision-Making. A Case Study".

The second case study was concerned more with the technical/scientific aspect of international environmental planning. The example presented is closely associated with the international regulation of acidification. Here an Integrated Environmental Model, named the RAINS model, plays a central role in developing different strategies for regulation of the problem, and provides direct input to the European negotiations on establishing an updated sulphur emission protocol. The model is presented as an important example of an Integrated

Environmental Model, and hence of the trend of today's technical/scientific representations. A sensitivity analysis was carried out on parts of the model relating to calculations of costs of emission abatement. Based on this experience, the model was analyzed in terms of applicability to practical decision-making. The analysis focused basically on finding a set of criteria for judging the applicability of such models. These criteria formed the basis for a model evaluation procedure which broadens the traditional evaluation concept. This case study was seen as another example of environmental problem-solving where models played a central role. The case study is presented in part three of the thesis which is entitled "Evaluation of Integrated Environmental Models. A Case Study".

It should be mentioned that the first case study is basically a result of literature studies, through which the environmental planning and decision-making processes and factors influencing them are analyzed by the author. As the implementation phase of the Water Action Plan was taking place during the period of the study, some of its aspects were followed simultaneously in the media. The second case study was performed solely by the author and fundamentally represents her experiences of working with and analyzing the RAINS model. During her time at IIASA, the author also participated in meetings held under the aegis of the United Nations and the Economic Commission of Europe (UN-ECE), where representatives (decision-makers) from the European Community and its member countries were present. During the meetings, the participants were shown various models and discussed options for emission reductions. RAINS was utilized parallel to the discussions and thus provided direct input to these. The meetings showed to a certain extent how RAINS was used at the international negotiations.

The present report summarizes the findings of the case studies and relates them to the hypotheses of the thesis. The report has the following outline:

Chapter 2 initially gives a review of the case studies in terms of the characteristics of the different planning and decision-making processes. The processes are compared and it is shown that they each represent processes where technical/scientific information (models) are applied differently. The role of models, or more specifically of Integrated Environmental Models, is discussed in terms of advantages and limitations. Additionally, a description is given of more fundamental differences in the planning processes depending on national/international differences, and on the actors in the three processes.

Chapter 3 identifies the uncertainty concept as a key factor influencing environmental planning and decision-making. Three different types of uncertainty technical, structural, and economic, are discussed in terms of the sources which cause them. A number of uncertainty elements are identified both on the technical/scientific and on the political/decision-making side of planning and decision-making. These are classified by sources of uncertainty and in terms of hierarchical importance. Methodological aspects of treating the elements are discussed in relation to real life decision-making processes as well as to the limitations of existing methods.

The conclusions and prospects for future research are presented in *Chapter 4*.

In order to avoid too many definitions directly in the text, the report includes an Annex outlining in detail the concept of mathematical models and more specifically Integrated Environmental Models.

The author has also been author/co-author of a number of publications and has presented lectures at conferences and courses during the study period. The following list presents the titles.

Publications and conference papers:

Sørensen, L, and Vidal, R.V.V., (1991): *A Critical Assessment of the Danish Water Action Plan.* In Fenger, J, Halsnæs, K., Schroll, H, and Vidal, V, (eds.): Environment, Energy, and Natural Resources Management in the Baltic Region. "3rd International Conference on System Analysis" Copenhagen, 7-10 May 1991. Nordic Council of Ministers, Copenhagen, 1991, NORD 48, pp 497-511. Article presented by L. Sørensen.

Amann, M., and Sørensen, L., (1991): *The RAINS Energy and Sulfur Emission Database, Status 1991.* Working Paper WP-91-xx, IIASA, A-2361 Laxenburg, Austria.

Amann, M., Hordijk, L., Schöpp, W., Sørensen, L., (1993): Economic Restructuring in Eastern Europe and Acid Rain Abatement Strategies. *Energy Policy,* vol. 20, no 12, pp 1186-1197.

Sørensen, L., and Vidal, V., (1993): *Evaluation of Integrated Environmental Models - Some Methodological Issues.* In Proceedings from NOAS '93, held in Trondheim, Norway, June 11-12, 1993.

Sørensen, L., and Halsnæs, K., (1993): *Aspects of Energy Planning - An Integrated Analysis of Multiple Environmental Consequences.* In Mander, U, Fenger, J., Oja, T. and Mikk, M. (1993): Energy, Environment and Natural Resource Management in the Baltic Sea Region - 4th International Conference on System Analysis, held in Tallinn, Estonia, May 18-21, 1993, Nordisk Seminar- og Arbejdsrapporter 1993:653, pp.125-136.

Lectures:

Critical Viewpoints on the Danish Water Action Plan. Presented at "Nordisk Forskarkurs" on Problem Structuring Methods, Reykjavik, Iceland, 2-8 June **1991**.

An Evaluation of Integrated Environmental Models Exemplified with the RAINS Model. Presented at "VI-Latin-American Meeting on Operations Research and Systems Engineering, Mexico City, 5-9 October **1992**.

All papers and lectures have been more or less directly used as basis for the case studies.

The author has also presented lectures at smaller meetings at the Institute for Mathematical Statistics and Operations Research (IMSOR), Lyngby, at the International Institute for Applied Systems Analysis (IIASA), Laxenburg, at ELSAM, Fredericia, at the Danish Environmental Research Institute (DMU), Roskilde, and at internal meetings at Risø National Laboratory where aspects of the thesis were presented and discussed.

2 Environmental Problem-Solving

Before going into detail with the decision-making processes of the case studies, it is necessary to define a few words and terms.

In the thesis a distinction is made between planning and the decision-making process. Formally, *planning* can be seen as a methodology for developing solutions to given problems. This covers a range of actions that seek to define goals and means of achieving them. The actions are usually supported by technical and scientific information (analyses), which is intended to end up in a plan (Lyngvig and Vidal, 1984). The plan consists of a set of relevant and feasible strategies and alternatives on which decisions must be made at some time, now and/or in the future (Rosenhead, 1989). The actions can either be about the physical siting of, for example, a building, or they can be of a more legislative type e.g. setting standards for "polluters". Planning is considered a part of the decision-making process. *The decision-making process* is used here about a process that has the overall aim of determining a strategy or controlling a given problem. It is the process where political goals for the planning are determined, where planning is carried out, and a political decision (commitment) is made (adoption of a plan on a national level). Basically, the distinction between planning and decision-making lies in the commitments concluding the decision-making process. *The problem-solving process* is used here interchangeably with the decision-making process. *Decision-makers* means a group including governmental officials, politicians, and technical advisors. Who actually is the principal decision-maker depends on the complexity and importance of the problem. Finally, throughout the thesis reference is made to a problem. This term basically refers to an *environmental problem* originating from human use of resources and resulting in undesirable impacts on the environment (ecosystems and human health). It is assumed that the problem is of a character which must be solved by some kind of decision-making process.

In the following, the planning and decision-making as it was conducted in the examples of the cases studies are compared and analyzed in respect of differences. The use and role of Integrated Environmental Models (or models in general) in the processes are also analyzed and discussed.

2.1 Review of the Case Studies

The case studies include three examples of real life environmental planning and decision making.

The first case study presents two decision-making processes resulting in formulation of national plans. *The Danish Water Action Plan* aimed at improving the quality of Danish surface waters through control and regulation of pollutants. Eutrophication problems had been discussed, analyzed, and even partly controlled for years. In 1986, a fresh impetus was given to the problem through extensive media covering and pressure from a non-governmental organization. The problem was brought to such a head that almost immediate political action was required to contain the governmental and parliamentary situation. Goals and means of solving the problem were determined during the open debate. Based on earlier technical and scientific findings, the Water Action Plan was formulated in a political environment, using only a minimum of scientific/technical material. In the implementation phase, the process and the plan itself have received extensive criticism from many sections of society. Through this criticism the decision-making environment, as well as the researchers' ability to perform satisfactory environmental planning and decision-making have been questioned.

The Dutch National Environmental Policy Plan (Dutch NEPP for short) aimed at establishing strategies for coping with the present and future environmental problems of the Netherlands. The most pressing problems were addressed through formulation of an integrated plan in which national problems were considered in local, national, regional, and global terms. A reputable Dutch scientific research institution with strong international links, pointed out the problems by publishing a report which attracted the attention of society. The report was taken seriously by the politicians who took the initiative to start more direct planning activities. Planning took place in close cooperation with the Dutch institution which provided all technical/scientific information to the decision-makers. Most information was obtained from model calculations. In spite of a rather efficient and successful process, the politicians came into serious conflict when the plan was to be adopted. The conflict resulted in the fall of the government and the plan was first adopted after an election and the formation of a new government. It was the first time in world history that a government fell on an environmental issue, and the instance shows how important such issues have become on today's agendas.

The second case study focuses on international planning at European scale within the framework of UN-ECE. It is concerned with the problem of acidification and finding ways of regulating by the establishment of a protocol for sulphur emission reduction. The acidification problem was described in an *Integrated Environmental Model* named *RAINS* (the concept of Integrated Environmental Models is defined in Annex 1,— the RAINS model is described in detail in Sørensen, 1994c). RAINS has been used throughout the planning process to analyze and identify relevant strategies for sulphur emission reduction. Model analyses have taken place parallel to the UN-ECE discussions and have provided direct support for the negotiations. At present the protocol has not been signed, meaning that the decision-making process is still in progress.

Table 2.1 summarizes some of the characteristics of the decision-making processes of the case studies. The decision-making processes are characterized by five central points: the focus of the problem; who raised the problem; the activities and participants in the planning carried out; the use of mathematical models in the process; and finally central points of the processes after adoption and during implementation in real life.

Table 2.1. Characteristics of the planning and decision-making processes of the case studies. Dutch NEPP is short for the Dutch National Environmental Policy Plan.

Case 1: The Environmental Decision-Making Process	Case 2: The RAINS Model
Problem: *The Water Action Plan:* National regulation of Danish polluters to improve water quality *The Dutch NEPP:* National development strategy to cope with all current and coming environmentally related problems of the Netherlands	**Problem:** International regulation of European acidification
Problem raised by: *The Water Action Plan:* The media and non governmental organization *The Dutch NEPP:* Scientific institution and initiative taken by politicians	**Problem raised by:** Scientists and technicians through the development of the RAINS model
Planning: *The Water Action Plan:* Mainly carried out between parallel political considerations, media pressure, and earlier technical/ scientific findings *The Dutch NEPP:* Carried out by extensive technical/scientific documentation as basis for political decision	**Planning:** Carried out with parallel technical/scientific findings from the RAINS model and international negotiations with the RAINS findings as basis
Use of model: *The Water Action Plan:* Model almost not used *The Dutch NEPP:* Integrated Environmental Models used to present problem, analyze the problem, and identify solutions	**Use of models:** The RAINS model used to create, and present the problem, to analyze, and identify solutions
Decision-Making and Implementation: *The Water Action Plan:* Plan adopted, extensive critique raised in the implementation phase *The Dutch NEPP:* Difficulties in adoption process. Plan adopted after the fall of the government and the forming of a new one	**Decision-Making and Implementation:** This phase still takes place

In the following, the second case study will be referred to as if the whole process had taken place. This means that the process will be assessed in terms of how the problem was raised and how the planning process has been carried out.

The three decision-making processes are characteristic ones in the way they were carried out and in their use of scientific information/models. Each of the processes illustrates one aspect or variant of traditional planning and decision-making.

On the one side, the process resulting in the Water Action Plan (in the following referred to as the Action Plan process) is shown. This process was highly dominated by the involvement of politicians and can be said to have been analyzed and solved in the decision-making environment and its surroundings; the problem was raised through the media and presented to politicians in the same media; initially, political actions were promised in an open debate; a non-governmental organization basically set the goals and means of solving the water problems; the points of the plan were formulated in the political environment; the decision-makers selected the scientific material to support formulation of the plan; the decision-makers took the initiative to both of the consensus conferences (before the adoption and in the implementation phase). Objections from the scientific side were ignored. Scientific information was used only to a limited extent, and the model providing the information was accepted by the decision-makers in spite of the many uncertainties associated with it (see Sørensen, 1994b for more specific comments).

Placed almost on the opposite side is the example of acidification regulation (the planning process will be referred to as the RAINS process). This process was/is highly dominated by the technical/scientific side through the RAINS model which was involved at virtually all stages of the process, RAINS has been involved: analyses with and publication of the results of RAINS highlighted the already existing acidification problem; through ongoing reporting on different strategies and impacts, decision-makers recognized the problem and initiated the process of creating international protocols; in the renewal of the first protocol, RAINS pointed to the complexity of the problem and to different strategies; RAINS has been accepted by, and used simultaneously with, the UN-ECE discussions. The scientists have serviced the decision-makers continuously throughout the process and the scientific findings have been utilized and judged in terms of their relevance to the problem.

Placed somewhere in-between the frames given by the other processes is the process resulting in the Dutch National Environmental Policy Plan (referred to as the NEPP process). The NEPP process was the outcome of more balanced interactions between decision-makers and scientists with the actions of each "group" lying very close to the traditions of decision-making processes. The problem was put forward by scientists, and the goals and means and intentions for how the plan should be formulated were expressed by the decision-makers. The initiative of designating the roles of scientists and decision-makers was taken by politicians. Political work held a low profile during the investigation of the problem. The scientists were working at high speed on a given job with a tight deadline. The results of the scientific work were presented to the decision-makers who then took them into consideration and interpreted them to formulate a political plan. This plan was a mixture of political goals and viewpoints, and scientific findings obtained by models. The complexities arising in connection with the adoption were purely between the decision-makers and their (political) goals.

2.2 Comparing the Processes

Comparing the processes in overall terms, there are some clear differences in the way they developed. One difference is the obvious rationality controlling the processes of NEPP and RAINS, in contrast to the trial-and-error irrationality of the Action Plan process. There can be many reasons for these differences, although the case studies point to two overall causes; the setting and constitutional framework for solving the problems; and the use of mathematical models.

Before going into discussions about the use and roles of mathematical models in the processes, it is necessary to discuss the overall differences between the frameworks of problem-solving. By framework of problem-solving is meant the constitutional framework within which the decision-making process develops. Based upon the experiences of the case studies, the author has identified two major factors determining the frameworks of environmental problem-solving in the examples given in the case studies, namely, national and international aspects, and the actors (different groups and their relationships) participating in and wishing to influence the process. These frameworks were different and may have contributed to the differences in the processes. The use and roles of models in the processes are discussed in section 2.3.

2.2.1 National and International Aspects

The international planning exemplified by the RAINS process is only one example of the increasing number of transboundary environmental problems and attempts to solve them. Within the European Community, environmental programmes have been formulated for years. There are several well-working international networks and councils which each have their groups dealing with relatively well defined problem areas. During years of practice a large variety of scientific and technical approaches have been applied in making the programmes (Vernon, 1993), reflecting the opinions of the participating decision-makers and the scientist groups supporting the decision-making, as well as revealing the difficulties in managing these tasks.

In overall terms, the conduct of international environmental politics can be viewed in a hierarchical framework consisting of five layers; local, subnational, national, multi-national, and global interests as illustrated in Figure 2.1.

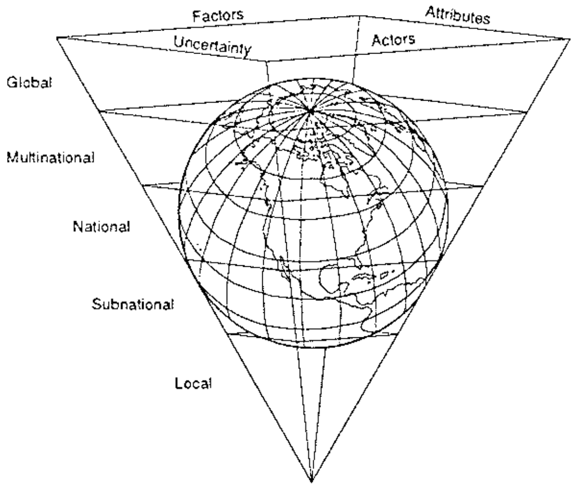

Figure 2.1. The different levels of global environmental policy-making (adapted from Wood et al., 1989).

Each side of the inverted pyramid represents an attribute of a given environmental problem or issue. The attributes chosen are the number of actors, the number of political jurisdictions (factors), the complexity of establishing knowledge on the ecosystems as well as political consensus (uncertainty), and finally the institutional obstacles in industry, the public, etc., to enforcement (attributes). For each layer, going upwards on the inverted pyramid, the variables become more numerous and their interactions more complex. At the local level causes and effects of environmental problems and actions to overcome them are relatively well known and well bounded, and decision-makers and analysts at this level are relatively clear about their roles and what is expected. At the subnational and national levels, decision-making becomes more contentious. Here it is more difficult to be clear about causes and effects, and who is doing what. Difficulties in getting an overview of the problem in a scientific way can be large, since the broader a system, the more variables and relations must be considered when describing it. Broadening the range of the problems increases the number of groups demanding influence on how the problems are solved. Conflicts of interest, agencies with overlapping interests and jurisdictions, competition between the various concerns of other lower hierarchical levels, all influence the decision-making. Going from national to multi-national and global levels, these issues become more evident, as international concerns must also be considered. This means that strategies affecting a large group of nations have to consider national jurisdictions, divisions of responsibility, unequal economies and technical resources, as well as the countries' sovereignty and acceptance of solving the problems.

At present, the authority of international environmental decisions is not of a legislative nature. It is left to the nations themselves to enforce the international decisions, and because of varying opinions on the Community as such and on the importance of environmental problems, national programmes are not always framed in accordance with international plans.

The tentative conclusion from these arguments would be that international and broadly scaled decision-making processes can be almost impossible to carry out, due to the large number of attributes involved compared with national decision-making processes. However, judged by the case studies of this thesis, this is not always true.

The RAINS process is one example of an international planning and decision-making process which seemingly has been carried out with a relatively large degree of success. With the constitutional framework of international negotiations, the author sees three reasons for this success. First, there is the experience of the international constitutional framework within which the environmental problems are solved. The European Community has, as already mentioned, a certain experience in formulating and negotiating environmental programmes and protocols. This means that the whole system of groups participating in the negotiations, time limits for finding solutions, and different methodological approaches to the determination of these have been defined and tried out in earlier situations. It is well known by all participants that problems can find some sort of solution in spite of the complicated settings where most countries must be heard. The second reason for the "success" may be that the international environmental protocols/programmes are not of a legislative type. Basically this means that the commitments made in, for example, an emission protocol, as illustrated with the RAINS process, do not have to be implemented in real life. Naturally, some sort of commitment is made by the countries signing the protocol, but the signatories cannot force another country which does not carry out the commitment in reality. It has been seen many times that a country signs a protocol and then afterwards makes excuses for not implementing it. The author believes that this lack of enforcement in connection with international environmental problems may be a facilitating factor for carrying out the planning and decision-making. Thirdly, the author also sees the scientific groups in the process as having a contributory role in facilitating the process. The scientific material utilized in the process has been provided from well recognized sources with international reputations. This means that the scientific material has been trusted by the decision-makers and that this may have prevented the rise of unnecessary confusion and uncertainty in the process. Naturally, the information given by RAINS has been discussed and criticized, but the model developers have continuously responded to the criticism — sometimes by changing the model in accordance with it.

Looking at the Action Plan process almost all these points are reversed. The Action Plan process was a national process in which the constitutional settings were rather different. Here the decision-makers represented legislators and their commitments had to be carried out in reality. With the definition of the problem and the level of importance it reached, the demands on the decision-makers were very high. Much was at stake, not only the politically unstable internal situation, but also the external national reputation. Until the adoption of the Water Action Plan, environmental problems had basically been solved in the Danish local governments (Miljøstyrelsen and Planstyrelsen, 1991). The type of problem that the Action Plan process addressed was relatively new, and there was no previous experience with carrying out that kind of planning. Additionally, Denmark has no scientific institution enjoying the level of reputation and recognition seen in the RAINS process (and the NEPP process). The selection of scientific material for use in the planning was made by decision-makers — perhaps imposed on the decision-makers through the 6-point-plan (see Sørensen, 1994b for more details). The scientific information was selected and used in accordance with the political goals. The author believes that these points contributed to the difficulties in the Water Action process.

Although the NEPP process also took place on a national level, it is very different from the Water Action process. In the Netherlands, the political process is different from those of Denmark and the Community. In the Netherlands there are two chambers where laws have to be passed by both chambers before adoption. This requires that the scientific information is in place and that it is provided by a recognised institution, as was, indeed, the case. Also, in the Netherlands environmental problems have been dealt with before on a national level, meaning that most of the process could be supported by experience of other plans.

The conclusion drawn from this small comparison of overall differences between the processes is that the processes were different mostly because of the political and legislative settings for the processes, and the experience and use of scientific material. These differences could be contributory factors for how the processes were carried out.

2.2.2 The Actors and Their Roles

Comparing the processes of the examples, it is evident that the actors participating also influenced the way the processes developed.

The case studies show that there are three major groups who actively take part in environmental planning both at national and international levels: the decision-makers and their surroundings, researchers, and non-governmental organizations and the media.

The decision-makers themselves play an obvious role in the decision-making process. This group is supposed to act rationally on problems to be solved, and to do this within the political and economic framework of their area (national or international framework). Since such groups consist of a diversity of people each committed to their own subjective preferences, political parties, etc., the role of the decision-makers can only be defined in a general holistic way. As illustrated especially by the Action Plan and the NEPP processes, the decisions of this group can be very dependent on internal power relations and conflicts between parties or smaller groups, but also between individuals.

In recent years, scientists have been engaged in finding facts about the cause-effect relationships surrounding the headline-making environmental issues. Their role in society is to provide a value-neutral series of facts. But with the increasing complexity of environmental problems, the relationships can only be outlined in non-accurate terms. Basically, it may be difficult for other social groups to realise that this is the situation, accept it, and then still understand that science has an important role to play. In the Action Plan process the scientific form never did get a strong role. Use was made of scientific material, but all objections to it were ignored, and there was no institution strong enough to change the situation. It should, however, be remembered that the scientific material used was not universally accepted among the environmental scientists themselves. Different persons and institutions expressed their views on the matter, leaving the public as well as the decision-makers with an impression of non-respect.

In both the NEPP and the RAINS examples the scientific community had the advantage of being accepted as the best (or close to the best) at knowing, understanding, and performing environmental analyses. The institutions behind RAINS and the integrated model used for NEPP are highly recognized and well reputed within the scientific world, as well as among decision-makers and other groups of society. This basically means that the material they provide is considered trustworthy.

No single comparable institution with such scientific reputation exists in Denmark. There are several different institutions performing similar types of research in competition with each other. The selection of the institution to rely on therefore depends solely on the preferences of the decision-makers.

In the case studies, the media and non-governmental organizations play a significant role, above all in the Action Plan process. More generally, these groups have the advantage of being able to create their own stage (places where discussions and confrontations take place) at well-chosen times. The media must be seen as a strong group in the societies of today, since in many situations they are the tools for communication of problems to decision-makers and of political arguments to the public.

Non-governmental organizations have almost the same role. They appeal to the public, they engage in research, lobbying, and organizing protest activities. They can concentrate efforts on single events and in these specific situations engage themselves totally on this event, provided the time is right, and there is a possibility that they will be heard or even achieve some positive response. Only through these actions, can the organizations show results of their work and justify their presence — and then gain more members.

It is not possible to make a rule defining which of the groups can be most influential on the development of environmental problem-solving processes. In the examples of the case studies, it is spread out almost evenly. The Action Plan process was mostly controlled by the media and the non-governmental organizations through the attention they gained in society. The NEPP process was controlled by the decision-makers though with a tight bond to the scientists. Finally, the scientists seem to be playing the controlling role in the RAINS process.

At the present time, the power relations (between the three groups and inside them) in society determine more or less how the process will evolve. The case studies indicate that these relations are particularly important when the problem is being raised and formulated. To be able to judge these aspects deeper, a more sociological analysis should be carried out. This is, however, outside the scope of this thesis.

2.3 Models, Roles, and Limitations

The differences in the processes as outlined above show that scientific analyses do influence the processes and their development. Looking at the examples, it seems as if the use of mathematical models (or scientific material in general) has been employed differently in the processes.

The model concept is used in various meanings about a representation of an object, an idea, or a system in a physical, verbal, or mathematical model (Shannon, 1975). In the present thesis, the concept of a *mathematical model* is used about a description of the behaviour of a system where its essential features are expressed in terms of a set of mathematical equations and implemented on a computer.

The thesis focuses on a specific type of model, named *Integrated Environmental Models (IEMs)*. Briefly, Integrated Environmental Models address environmental issues through a multi-disciplinary approach describing the relations between causes and effects. In practice this means that an IEM is constructed as two or more submodels (smaller models) that are linked in some way. Each of the sub-models represents one small area of the system to be described, and they therefore commonly represent different fields of science. The submodels are usually built on different mathematical approaches based on field specific variables, and parameters. Often the IEMs aim at supporting policy management through developing scenario strategies that can be analyzed in the planning process. The second case study (Sørensen, 1994c) refers to the RAINS model, which is an example of an IEM. In Annex 1, the concept of Integrated Environmental Models is defined and described in more detail.

Naturally, the use of models is a way of visualizing the complicated processes of environmental issues. The model can become an educational tool for teaching the scientists about causes, relations and effects, but certainly also for teaching the non-scientists about these things. At the same time, the models represent the core of many scientific disciplines; it is a way of showing the results of research and make it clear that something operational comes out of these activities. Subsequently the models can be used in the decision-making surroundings with different overall purposes.

Going back to the case studies, there is a clear difference in how the models of the scientific environment have been used. In each of the examples there is a certain acceptance of using the models,— acceptance of the fact that this is the way the scientific side obtains and develops information. In connection with the Action Plan process, the model (and its results) was afterwards exposed to heavy criticism. Knowing that the work of the institution developing the model had already been questioned (through the evaluation of the Danish research standard) one can ask why this particular model and its results virtually *had to be* used. Naturally, the availability of the results in the given situation played a role, as already mentioned. But looking closer at the process, it seems as if the decision-makers were in a situation where their goals and means had been imposed on them by a non-governmental organization, and therefore, almost by definition, were surrounded more with emotional and political objectives than with facts. The choice of using the model results can then be seen as an attempt to get some rationality into the decision-making process, and through this rationality to justify the goals and means of the plan.

The rationality aspect is more evident in the NEPP process. Here IEMs were used for developing the goals and points of the plan. That the models were used at all was basically a choice of the Dutch institution and was therefore not questioned, since the institution was highly respected and its work considered trustworthy. The methods or tools for obtaining the results were not questioned either. The model used in this process can be seen as having a supportive role for the decision-making process.

The RAINS example shows that the use of models can be decided more or less directly in policy discussions. This example shows that models can become very influential tools; the problem was defined and formulated based on the scope of the model; discussions were initially focused on the aspects that were analyzed by the model. This way of using models offers the possibility of a certain control of the decision-making process and its evolvement. Thereby, models can become an element in society, influencing or setting the prospects for the decision-making process.

In each of the examples of the case studies, models appear to have been given a certain role in the planning and decision-making processes. In the Action Plan process, the model calculations were used in spite of the relatively large uncertainties associated with them. Fundamentally, these model results lay behind the political goals of the plan. The whole process was a very political one, as already mentioned, where it may seem as if these specific results were selected simply because they fitted well into political frames and the way political goals were expressed. No attempts were ever made from a political side to seek second opinions on the scientific issues. To the author it seems as if the selection and use of these scientific findings had a justificative role in making the specific decisions. Not only did the model results support the political decisions, but they also offered the "necessary" (traditional) scientific considerations requiring a plan. It looks as if the model results offered an immediate justification of the decisions on the plan, but at the same time also should be the basis to which the decision-makers could point if their decisions turned out to be non-effective. The criticism raised after the adoption and the second consensus conference concentrated on the scientific knowledge and not on the political decisions,— the scientific content of the plan became a sort of scapegoat in the process. Using models and scientific material in this way can be said to give them a justificative role for the decision-making process.

In the NEPP process, the models were used differently. Here they were trusted and used directly as providers of information to the decision-makers. But as the scientific and the decision-making environments were separated, the scientific material became a sort of supportive information for the decision-makers. The models were used by the scientists who then communicated the results to the decision-makers. The NEPP plan was formulated on the basis of these results which must therefore be said to have been supporting the decision-making. In contrast to the Water Action Plan, the way the models were used in formulating NEPP made them supportive. Therefore the model, when used in this way, can be said to represent a supportive role in the decision-making process.

The RAINS process also used models actively, but again differently. Here the model was utilized parallel to and directly in the decision-making process, where both scientists and decision-makers participated. It is not possible to specify the role of the model in this process, but it is clear that the model results have been used in the international discussions. The RAINS model has been accepted for use and has perhaps also been allowed to set the perspectives for the discussions. The way RAINS was used can seem as if the model to a certain extent was steering the discussions. Used in this way, models can therefore be said to have had a steering role in the decision-making process. That the model is steering the discussions should not necessarily be seen as a negative role. Especially not if the alternative is that decision-makers cannot agree on making a decision.

It should be mentioned that if a model is used like the RAINS model, the planning and decision-making process in its traditional aspect is far from being followed. The scientific context becomes a factor which is far more than support for the decisions to be taken. It is an open question whether the traditional frameworks of the decision-making processes of today can cope with a more steering roles of science.

The examples of the case studies show that models play a role in environmental decision-making processes and that their use is very closely associated with a rational decision-making process.

However, when using such tools there are some obvious limitations on how they can/should be used in real world planning and decision-making. The case studies show that there are several limitations on using models in environmental problem-solving and that these can be attributed either to the models themselves, or to those who use them.

2.3.1 Limitations in the Models

Within the models themselves, there are several aspects that can limit their use in practical decision-making.

First, there are the difficulties in getting an overview of the models because of their large structure. Integrating modules and submodels into an Integrated Environmental Model results in a model structure, which is large and includes various mathematical expressions and technical terms from different scientific fields (see the RAINS model in Sørensen, 1994c). Working with the models, it soon becomes clear that they can be hard to understand fully in terms of what they can do, how they do it, what they cannot do, the assumptions behind, etc. This phase of getting to know the model can take much time, and usually any user of the model only gets to know smaller parts of the model very well, while the rest of the model is known only in general terms.

One thing is the large structure of the model, another is the level of detail included in the various submodels. Models of differing detail appeal to different people. Some people will like a very detailed model focusing on one specific area, while others will prefer a simpler and less detailed model to provide an overview. The variations found in Integrated Environmental Models may therefore appeal to different people and influence their acceptance of them.

Relevance to the problem is another aspect. It is important that the model address the problem in a such way that the strategies or solutions found by the model has relevance for the decision-makers. This means that the model must be kept up to date with the way discussions are going in the decision-making agendas, and that it includes the best scientific knowledge available. This is not always the case (see the debate about the Danish Water Action Plan in Sørensen, 1994b). Sometimes the models are applied to situations for which they were not intended. This may give a wrong impression of the model and of scientists as a whole and affect the extent to which the models are applied.

The presentation of the model results and evaluation (see Chapter 3 for more detail about these aspects) of these, must also be mentioned as sources of problems with the models. The way the model is presented to its users is through the results and analyses made by means of the model. It can lead both to confusion, misunderstanding, and resistance towards the model, if the results of the calculations are not presented in clear, unambiguous ways. The Integrated Environmental Model is a model type where this can perhaps be difficult, since there are several parts of the model from which results can be obtained. The evaluation of the model must also be available to the user in a clear way. Clarifying the assumptions behind the calculations and the model structure, and the uncertainties of calculations are aspects which contribute to the impression of credibility and acceptability the user is given of the model and its results.

Lastly, the systems analysis approach should be mentioned as a possible constraint in the use of the models. *Systems Analysis* can be defined in various ways. One definition is "*an analysis to suggest a course of action by systematically examining the costs, effectiveness, and risks of alternative policies or strategies - and designing alternative ones if those examined are found wanting*" (Quade, 1963—in Jackson, 1991). Systems Analysis developed during the 1940's and applications of this way of thinking were made in the 1950's in the military sector. Nowadays the systems analysis approach is being applied to most problem areas — also to environmental problems. Different versions of this approach are employed in government departments and agencies, in local authorities, in business and in educational institutions all over the world. The approach has proved relatively successful when applied to well-defined problems (Rosenhead, 1989). Most Integrated Environmental Models are developed from a systems analysis angle. The *mechanistic principles*, i.e., where the systems in focus are represented by separate distinguishable submodels each contributing equally to the description of the system, have their limitations. It is argued in many sources (see for example Rosenhead, 1989, and Jackson, 1991) that the systems analysis approach has many limitations for application to types of problems like the environmental ones. There are underlying assumptions about the quantification of all processes — also human ones: that the models consider everything which is useful to the decision-making, that the decision-makers act in a rational way, and that the problem can be solved by using the methodologies.

2.3.2 Obstacles to Practical Use

The complexities of the decision-making environment is another dimension that can influence the use of the models. This problem has several aspects:

First there is the individual's resistance to the use of models. This can be caused by resistance to computers and new technology in general. Another aspect is the belief that the model takes over the role of the decision-maker and wipes him/her off. Other factors may be lack of confidence in the scientists who developed the model, in the structure of the model, or in the assumptions and/or the calculations of models in general.

Secondly, there is the problem that several people have to agree on which specific model to use. The environmental decision-making setting includes many people and institutions, among whom there may be smaller or larger conflicts. The conflicts can be about the model itself or, more likely, about political and subjective preferences.

The third dimension is closely connected with the multiciplicity of aspects/criteria to consider in making environmental plans. The environmental aspects as covered by the Integrated Environmental Models are only one part of the social issues requiring attention. There are other pressing questions than the environmental problems to consider simultaneously. The Integrated Environmental Models cannot be used for this sort of *multiple criteria decision analysis* (see Wallenius, 1991) where the costs and benefits of selecting various combinations of plans or strategies are analyzed.

As already mentioned, the analyses and policy processes are performed almost independently by different people. The models can then be seen as tools of communication between the different groups. It is well-known that there is a gap between the scientific and the decision-making environments, and that there are problems with mutual communication (see for example Guariso and Werthner, 1987—and the Action Plan process).

The structure of societies are built on a compartmentalized way of handling various problems. An analysis of one problem is performed at some specific institutions and formulated in the relevant ministry. If the same problem is formulated in a slightly different way, it will be analyzed by another institution and perhaps formulated in another ministry. The whole structure of society is based on this kind of compartmentalized structure, where some people provide the information to be used by other people who then decide the courses of action.

The limitations mentioned to the use of models in the decision-making process are not always recognized and handled in some way. It is shown that in the Action Plan process, the limitations have been overlooked and the model results were used. If the model/model results are used without regard to these limitations, uncertainty can arise and influence the planning and decision-making.

2.4 Summary

The examples of the case studies are seen to represent different decision-making processes where mathematical models have been used with varying degrees of succes. The Action Plan process is characterized as a highly irrational process where models (model results) were used very little. The Dutch NEPP process is seen to be an almost ideal process, following the traditions of problem-solving processes to a large extent. The process used models in a supportive fashion where the scientific context provided by models was acknowledged and fully accepted by all parties involved. The RAINS process also involved the use of models. Here it seems as if the use of the model was of a much more controlling character, where the problem had been created and analyzed using the model concurrently with policy discussions.

The national and international frameworks for solving the problems as well as the actors and their power relations are all factors determining how the decision-making process can evolve. However, it is not clear from these studies how these factors control the process in more precise terms. Models can be seen to represent certain roles in each of the examples of the case studies. In the Action Plan process, the non-use, and yet use, of mathematical model results was exploited to justify the political decisions. In the Dutch NEPP process, models were used to a large extent. Here the models had a supportive role in the decision-making process. The RAINS process was characterized by even closer involvement of the model. Here the model can be said to have played a somewhat steering role in the decision-making process. Since the conventions of traditional planning and decision-making consider the scientific contribution to be of a supportive nature, the use of models can create processes that are highly different from the traditions of decision-making.

There are many limitations on the use of models in practical environmental planning and decision-making. The limitations can be attributed to the models themselves, or to their users. It is necessary to focus on these limitations before using the models/model results in planning and decision-making. Otherwise uncertainty can arise and influence the process.

3 Uncertainty

In the case studies uncertainty has been identified as a major factor influencing both the scientific and the decision-making sides of environmental problem-solving. This was particularly evident in the Action Plan process as outlined in Sørensen (1994b). However, uncertainty was also present in the other processes where the uncertainty aspects either were handled in some way or disregarded.

This chapter is devoted to analyzing the sources that can raise uncertainty and to discuss limitations of existing approaches (mainly mathematical methodologies) for coping with this uncertainty.

"Uncertainty" is a concept which has existed in scientific literature for several decades. It is a broad ranging, almost charismatic concept, which encompasses the inaccuracies in physical and mathematical descriptions of natural processes as well as fundamental incommensurability as a general characteristic of today's life. In the last decades, the uncertainty concept has been applied to all technical, scientific fields as well as the social sciences and has been recognized as a central issue that cannot be disregarded. In the thesis, uncertainty shall be understood in a broad sense as "lack of sufficient knowledge about past, present, future, or hypothetical events" (Fiddle, 1980). Uncertainty can be used in association with a model quantity (values, relations between quantities, etc.). Uncertainty can also be associated with a decision and its outcome. Since the uncertainty concept is highly ambiguously defined, uncertainty is also used throughout the thesis (the present part as well as the case studies) with different meanings. In general, uncertainty is associated with, for example, a quantity of a model, meaning that the quantity is associated with a certain variance (statistical or natural), randomness, or even error, which can be estimated in quantitative terms. Uncertainty about a decision is used more about the unpredictability of the effects of the decisions made. This uncertainty can obviously not be subjected to a quantitative estimate. Furthermore, uncertainty is also used about the approximations made in, for example, describing a problem where deviations are made from the real world. And finally, uncertainty is used about situations where linguistic imprecision affects, for example, a debate, or about disagreements arising between people and groups with differing opinions. It is not possible to be specific about what is meant with "uncertainty" every time the concept is referred to. It is hoped that it will be relatively clear in the text which specific meaning is referred to.

As a result of the first case study, three types of uncertainty closely associated with the problem-solving process were identified. As mentioned in Sørensen (1994b), the types were technical, structural, and socio-political uncertainty. *Technical uncertainty* can be attributed to the formal description and analysis of a problem. This type of uncertainty is mainly attributable to model components, results of model calculations (quantities such as variables and parameters) and the equations used to obtain and describe them. Technical uncertainties can in fact be associated with almost all of the above mentioned meanings of uncertainty. In the literature there is, however, a tradition of referring to model uncertainties in the meaning of variance, randomness, error of quantities, or approximations imposed from the real world with the model equations and borders of the system modelled. When referring to uncertainty analysis in the following and in Sørensen (1994c), the analysis is concerned with identifying and quantifying or otherwise describing these uncertainties.

The second type of uncertainty is identified as *structural uncertainty* which can be attributed to the way the problem has been structured and approached in the search for solutions. This type of uncertainty arises as a consequence of the boundaries set for the system surrounding the problem, as a consequence of the problem definition and the scientific discipline and method for approaching the problem. Structural uncertainty refers mainly to the meaning where approximations are made from real-world processes.

The third type of uncertainty was identified as *socio-political uncertainty* which is attributable to the more human and social linkages, interactions, and conflicts arising in the decision-making and scientific environments as well as between these. Different perceptions of a problem, subjective preferences and priorities, and conflicts are all points causing socio-political uncertainty and making the results of the process more unpredictable. Here the meaning of uncertainty is linguistic imprecision, disagreements and general lack of knowledge about scientific relations, and effects of decisions.

In the case study Sørensen (1994b), the uncertainty concept is used in all three meanings. The RAINS case study (Sørensen, 1994c) focused more on technical and structural uncertainties.

The types of uncertainty and the distinction between them are not always unambiguously determined, since one uncertainty type may be more or less a direct consequence of another uncertainty type. An example can be found in the Action Plan process where uncertainty in model calculations (technical uncertainty) resulted in an increasing level of conflicts between involved parties and groups. These conflicts raised uncertainty (socio-political) about where the process would end. For the same reason it is also difficult to assess which types are more influential on such processes. It is, however, one conclusion of the first case study that socio-political uncertainties may be the most influential and difficult to handle (see Sørensen, 1994b).

The identification of the types of uncertainty has, however, little value if the sources from which uncertainty arise are not identified.

3.1 Uncertainty Elements

An *uncertainty source or element* is a factor from which some sort of uncertainty can arise. In Sørensen (1994b) this concept was already introduced in comparing the Action Plan process with the NEPP process. In Sørensen (1994b) several examples are given of uncertainty elements.

Generally, one can distinguish between uncertainty generated by technical-material factors (in this thesis by models) and uncertainty generated by people's perceptions. Regarding the formalized decision-making process as a two level process, the scientific side and the political side, a classification of general uncertainty element groupings can be made within these.

3.1.1 Model Uncertainty Elements

In the literature several attempts have been made to classify uncertainty elements associated with models and modelling. Of publications should be mentioned: Morgan and Henrion (1990) who identify several model quantity aspects that may raise uncertainty; Ronen (1988) who operates with two classes for description of data uncertainty; Beck (1987) classifying several quantities connected with model calculations that can raise uncertainty; Funtowicz and Ravetz (1990) who identify three types of uncertainty associated with scientific practice in general; Friend and Hickling (1987) who operate with three broader types of uncertainty associated with the decision-making situation as such; Alcamo and Bartnicki (1985) who identify model components that are likely to raise uncertainty.

Even though scientific results are often judged in terms of *uncertainty analysis* and description of uncertainty elements, there exists no standard or consensus on how to classify these as well as model uncertainty sources. Studying Integrated Environmental Models it is, however, obvious that it is necessary to operate initially from a sort of uncertainty classification since the number of sources may be enormous.

Table 3.1 outlines a proposed taxonomy, a classification of model uncertainty elements as they have been identified by the author from the case studies. It should be mentioned that Alcamo and Bartnicki (1985) operate with an analogous but less detailed taxomony. The uncertainty sources are associated with all model components of Ingrated Environmental Models.

Table 3.1. Classification of sources of modelling uncertainty.

Model Uncertainty Element	**Comment/Explanation**
Model structure	The frames for the description, submodels (modules, disciplinary view on the problem
- Diagnostic description	- Description of past and present behaviour of the system
- Forecasting description	- Prediction of future behaviour of the system
Parameters	Quantities that are not changed by operations of the model
Defined	- Well-known constant given by fundamental scientific considerations or definitions
Estimated	- Constant estimated through mathematical tools
Value	- Constant that cannot be measured or defined unambiguously. Represent the preferences of the model developer
Variable	Quantities describing the state of the system and sub-systems
Empirical	- Quantities that are somehow measurable (or in principle measurable)
Decision	- Quantities that cannot be directly measured in technical, quantitative terms and must be judged or otherwise assessed
Functional relations	Describe relationships between the variables and parameters in such a way that they reflect the behaviour of the system
Criteria functions	- Functional relations that express explicit statements of the objectives or goal of the system and how they are evaluated
Constraints	Limitations imposed on each of the model components
Initial state conditions	- The specific starting values for which the model calculations are initiated
Model operations	The specific numerical solution techniques of the functional relations and criteria functions
Model output	The model result and how it is expressed to users of the model

The selection of the *model structure* is the fundamental uncertainty source in a model. With the model structure, the approximations from the real world and the assumptions about the behaviour of the real world are introduced. Here the scientific background of the modellers play a central role. Researchers from different fields of science tend to see the world differently when viewing the central keypoints of a particular system, the aggregational levels, the time perspectives, selection of model type, etc., etc. All points introduce approximations from the real world's processes and systems. It is the model structure that impose the border of the systems to be analyzed — and through this the fundamental assumptions about these are made. These aspects may show in the form of inaccurate or imperfect behaviour of the model, and thereby give insufficient results of model runs. *The diagnostic description* and *the forecasting description* can raise uncertainty mainly in the form of quantity uncertainty. These two elements are closely associated with the selection of model type, the functional relations, constraints, variables, and parameters for the description of the time perspectives. In principle, the model may be different for describing different periods of time.

The parameters can be a source of various uncertainty types. *The defined constants* are quantities which are taken as a result of scientific consensus and have almost per definition no uncertainty associated. *The value parameters* are mainly based on subjective preferences. Uncertainty raised in connection with the value parameters can be due to factors such as approximations from similar figures, and disagreements between scientists or decision-makers. *The estimated parameters* are more closely linked to the general factors of error and variance, approximations and again disagreements, perhaps about the methods for estimation of the parameters.

The variables are almost analogous to the parameters. *The empirical variables*, which in principle are measurable, may be sources of uncertainty due to the general meaning of uncertainty as: error, variation, randomness, approximations, linguistic imprecision, disagreement. It is usually attempted to describe these aspects some way through uncertainty analyses. *The decision variables*, which not are measurable, are mainly a source of uncertainty because of the approximations made from similar linguistic imprecision when reporting on relevant measures.

The functional relations are a source of uncertainty due to the basic selection of approach for describing the dynamics of a system. As for the model structure, the functional relations are closely associated with the disciplinary basis for description of the whole system and the approach considered for its description. Factors such as approximations of natural processes into mathematical and numerical descriptions and disagreement about this selection are the main reasons for the uncertainty that may be raised. It should be mentioned that functional relations are often used in the "linkage" between various submodels or modules in Integrated Environmental Models. The functional relations hereby play a central role in the model since it describes both the smaller systems and the linkages between these. Additionally, it should be mentioned that the functional relations play a role in the model, when uncertainties from the different model component/uncertainty sources are propagated through the model and end up in the model result. Therefore, it is of interest to determine which sources influence the results the most.

Similar to the functional relations, the *criteria function* may also be a source of uncertainty. The criteria function aims at expressing *the solution* of the problem to be solved and hereby the fulfilment of the goal of the analysis. Especially, with the large environmental problems, which comprise aspects of the environment, socio-policy, economy, and other factors, the criteria function can be a large simplification of the real problem when only one aspect is described. This may give rise to uncertainty about the relevance of the solution based on the function.

The constraints put on the model description may raise uncertainty in itself, mainly by imposing approximation on the system. One important aspect of the constraints is the initial conditions setting the range for the performance of the algorithms of the model and thereby the range of the system. In the last decade increasing attention has been paid to the effects of the *initial state conditions*. It looks as if the selection of the initial state conditions for starting the model calculations may, in extreme situations, cause model results that are many times (200-300%) either too large or too small. The initial state conditions may have a significant influence on how well the algorithms of the model perform and thereby also on the accuracy of the model results.

The model operations as such can raise uncertainty because of limitations in the numerical representation of mathematical descriptions, and the algorithms can be regarded as additional approximations from the real world processes.

Naturally, *the model output*, i.e., the values, graphical pictures, strategies and the perception of them, is the uncertainty source which commonly is the focus. The output must be viewed upon as a composite measure where all (or most) model components have been involved. Uncertainties associated with individual model components are propagated through the model by the model equations (as already mentioned), and the composite uncertainty is expressed through the model output. It is important to note that uncertainty connected with model output is not only of a technical kind. All types of uncertainty may be raised from the model output measures, or strategies. Especially, it should be mentioned that the model output often can be seen as a source for judging the whole problem analysis, since disagreements about a result can lead to questioning of the previous steps of the analysis.

All factors can raise almost all types of uncertainty. However, in Table 3.2 are depicted the most common types of uncertainty raised from the elements.

Table 3.2. The model uncertainty elements and the most common type of uncertainty raised.

Source of Uncertainty	Type of Uncertainty
Model structure	Technical/structural/socio-political
Parameters	
Defined	No uncertainty
Estimated	Technical
Value	Technical/Socio-political
Variable	
Empirical	Technical
Decision	Technical/Socio-political
Functional relations	Technical/structural
Criteria functions	Technical/structural
Constraints	Structural/technical
Initial state conditions	Technical/structural
Model operations	Technical/structural
Model output	Technical/structural/socio-political

Arguments for this construction have already been given in the preceding text.

Naturally, not all sources have equally high importance and influence on the model as a whole. The uncertainty elements must be assessed individually and judged in terms of how significant their influence is on the calculations and output. As seen by the author (with the experiences of the case studies in mind), a tentative hierarchical ranking of the uncertainty elements can be made and is showed in Figure 3.1 (Alcamo and Bartnicki, 1985, have an analogous hierarchical ordering).

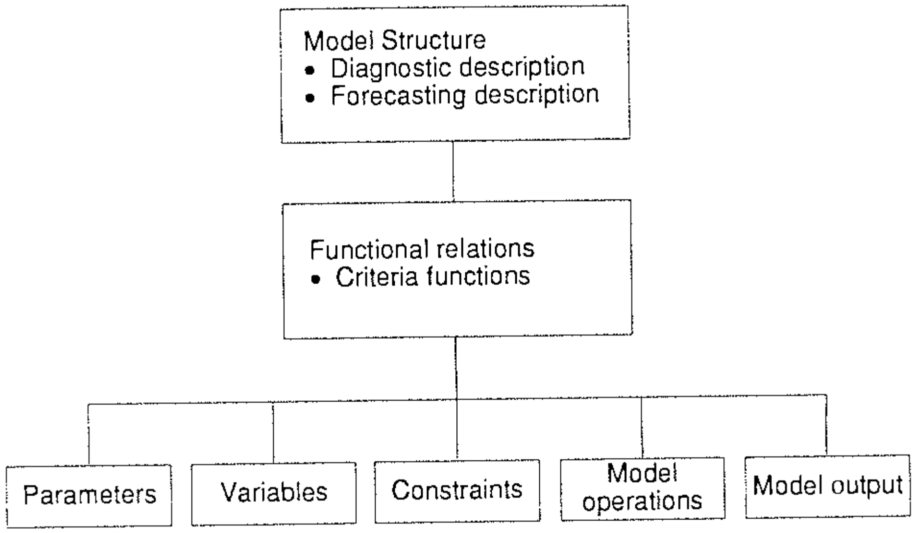

Figure 3.1. Hierarchical ordering of model uncertainty elements.

Figure 3.1 shows that uncertainties due to the parameters, variables, constraints, model operations, and model output are dependent on the model's functional relations and above all on the model structure. It does not, however, say anything about the influence of the single elements. It should be noted that for example two uncertainty elements taken as a whole do not necessarily contribute to making the model calculations more uncertain. Some elements may influence the calculations in different, opposite directions so the total result becomes a level of almost negligible uncertainty.

Although it is important to focus on the model uncertainty sources, one conclusion of the case studies is that uncertainty within the policy making environment are more important and influential on the process.

3.1.2 Policy Uncertainty Elements

When uncertainty associated with decision-making is considered in the scientific, mathematical literature, the problems of choosing a strategy are often seen from a game theoretical aspect (Keeney and Raiffa, 1976), where it is attempted to give a quantitative score on various decisions made by various people and based on mathematical arguments. However, it is also recognized in the literature (see for example Wallenius, 1991) that the methods are difficult to apply to environmental decision-making situations. The difficulties in predicting the outcome of a decision situation are also recognized in the sociological sciences (see for example Fiddle, 1980) where it is attempted to understand the behaviour of human beings in such situations. In neither of the fields has it been attempted to classify the different policy uncertainty aspects. Looking upon the Action Plan and NEPP processes, it is obvious that there exists a number of sources that may influence the processes severely (see Sørensen, 1994b). The following Table 3.3 summarizes and specifies different policy uncertainty aspects as seen by the author.

The elements are chosen as a direct result of the case studies and the arguments

Table 3.3. Central policy uncertainty elements associated with environmental decision-making.

Policy uncertainty elements	Comments
The problem presentation importance urgency	The type of problem to be dealt with, how it is presented for the people who takes initiative for solving it, how important it is considered and with which urgency it must be solved
The problem-solving environment	Place of where decisions must be made, the groups/people involved
The models	The model represents the more technical and scientific analysis of the problem - and the corresponding solution found
Information	The exchange of information between the different groups of the problem-solving environment and the outside groups which also could be interested in the problem
Conflict	The disagreements between and in the problem-solving environment, their subjective and objective viewpoints and their willingness to cooperation

and discussions in Chapter 2 of the present report.

The problem to be dealt with is a key point for raising uncertainty of a socio-political character, mainly in the meaning of linguistic imprecision, disagreements and lack of knowledge about effects of decisions in general. Special factors which may cause that, are the presentation, the importance, and the urgency of the problem. Under special circumstances, *the presentation of the problem* can create the setting for the decision-making process through the reactions that are evolving in the society. This presentation is one factor determining the decisions that groups make for solving the problem. If the presentation is made in a popular style (for example through public media as with the Action Plan process) it can be difficult to define who specifically has an interest in the problem. It may be likewise, if the problem is presented in highly scientific terms making it difficult to understand for non-scientists. *The importance of the problem* is a direct outcome of the presentation. Through the presentation, the importance of the problem is also set initially. However, this initial level may be changed according to reactions from interest groups and how successful they are in expressing their interest (see the role of the media and the Society for Nature Conservation in the adoption process of the Danish Water Action Plan (Sørensen, 1994b). And as a direct result of the importance accorded to the problem, the element of *urgency* turns up. The time perspective for dealing with the problem is a factor that can raise much uncertainty. The level of urgency can determine which groups of interests will be heard in the decision-making process, at what level a technical/scientific analysis can be made, and what pressure to put on the decision-makers. It is to a large extent the problem that initiates and controls the whole problem-solving process: the operational problem formulation is based on the presentation, the political and scientific goals are determined, the level on which the problem can be analyzed is to a certain extent determined, the scientific disciplines to involve are set as are the decision-makers to be involved, and through the importance and urgency the pressure on the involved groups is given.

The problem-solving environment is another key factor for raising uncertainty. The groups and individuals participating in the handling of the problem may in themselves raise uncertainty. This uncertainty is closely related to the constitution of the involved groups and individuals, how they subjectively view the problem and the other groups and individuals, how good their reputation is in the area, how precisely the different roles are defined, and above all the political level where the decisions are made. Mostly, this uncertainty is of a socio-political nature. These aspects are closely associated with the factors that may influence the planning and decision-making as was discussed in Chapter 2.

Regarding *models* as tools for analysis of the problem and for formulation of goal oriented solutions, this is another factor for raising uncertainty. Uncertainty can be raised as a consequence of how the model, its results and the modellers are looked upon by the decision-makers. Some decision-makers may question the use of this kind of "technology" and thereby create uncertainty about the use of the models. The models can also raise uncertainty because they reflect a question which is irrelevant to some decision-makers who then will question the use of the model. The model may also produce a result which is not in accordance with more general political perspectives and can then be the cause of socio-political uncertainty (what do the scientists mean?). Finally, the model can represent a highly scientific environment. If the scientists fail to communicate the results of the analysis in more intelligible ways, technical and socio-political uncertainty can be raised as a result of misunderstandings (or more precisely linguistic imprecision).

Information is another factor for raising uncertainty. Throughout a decision-making process, great deal of information of all kinds will be exchanged between and within the political and scientific environments as well as to the surrounding society. This exchange of information can be influenced by many factors such as linguistic imprecision in exchanging oral information, and deliberately made approximations of figures, etc. The exchange of information may be closely associated with how well the process develops.

Finally, the factor of *conflict* must be singled out specifically. Disagreements of various kinds, lack of willingness to cooperate, subjective views on the problem, the importance and urgency of the problems are all factors which may create conflict and lead to uncertainty about the outcome of the process. Conflicts can be of varying scale; between two single individuals, or between nations and can therefore also be of varying importance to the problem-solving.

In Table 3.4 is summarized the uncertainty elements of decision-making and the key types of uncertainty they raise.

Table 3.4. The elements of policy uncertainty and the type of uncertainty that commonly is raised.

Policy uncertainty element	Type of Uncertainty
The problem	Socio-Political/structural/technical
Problem-solving environment	Socio-political
The model	Socio-political/structural/technical
Information	Socio-political
Conflict	Socio-political

Again it is difficult to judge which elements influence the decision-making most. However, a hierarchy of the elements is presented in Figure 3.2 based on the previous reasoning and the experiences with the case studies.

The problem is regarded as the factor that sets the framework for the analysis and the problem-solving environment. Under this the other factors, the model, information and conflict may evolve.

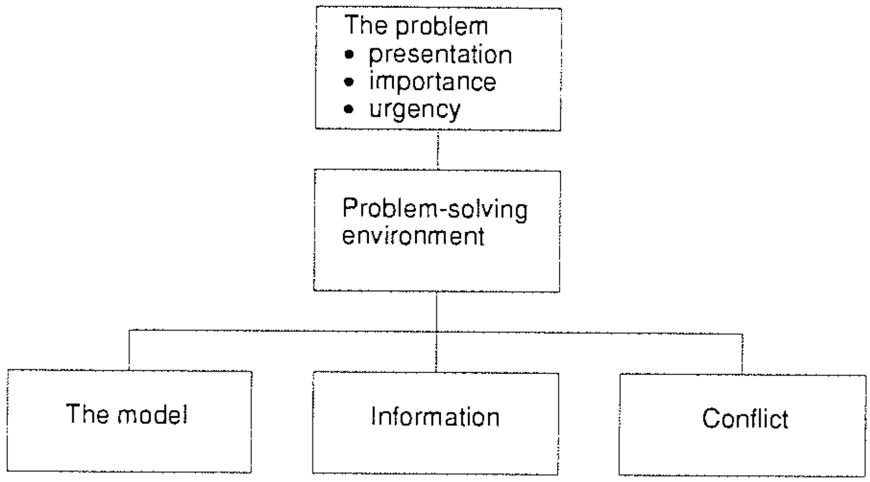

Figure 3.2. Hierarchical ordering of the policy uncertainty elements.

3.2 Methodological Considerations and Limitations

As it follows from the case studies, uncertainty is an issue that is bound to exist in decision-making processes and to have some sort of influence. The decision-making environment faces large uncertainties which may be impossible to control, while the models have a great number of uncertainty sources which propagate uncertainty through the model and affect its results in almost opaque ways. If one considers the case studies and the discussion in Chapter 2, it follows that management of uncertainties is important if one wants to ensure a certain level of rationality in the decision-making process.

As the elements are presented here it looks as if they can be unambiguously identified. This is not the case. Many of the elements are interlinked, and if one uncertainty element is removed in some way, another may be handled simultaneously. It is therefore important to find the relevant elements to focus on.

The scientific literature is mostly concerned with uncertainties of a technical type, and more specifically single uncertainty sources attributed to model components are addressed. As outlined in Sørensen (1994c), the framework for addressing and handling model uncertainty sources is called *model evaluation*. The traditional way of performing model evaluations is, as mentioned in Sørensen (1994c), associated with examining the model in terms of *verification* (check of the model behaviour), *validation* (checking if the structure of the model behaves realistically), and *sensitivity* (determination of the importance of changing various model components and noting the magnitude of change in the output results) and *uncertainty analysis* (comparison of the model's inherent uncertainties in terms of their relative contributions to uncertainty in the output results). It was concluded in the case study that these traditional frames not were sufficient to secure that influential uncertainties were dealt with. This will be outlined in more detail in the following.

A very common way of evaluating models (also IEMs) is to perform sensitivity or uncertainty analyses of selected model components. As already mentioned (see Sørensen, 1994c), sensitivity analyses cannot give an estimate of how uncertain the model component is. Sensitivity analyses only say something about the *robustness* (flexibility of the model output when changes in input are made). It is commonly seen that sensitivity analyses are interpreted as uncertainty analyses. This is seen for example in some of the publications reporting the analyses of the RAINS model as outlined in Sørensen (1994c). The view of the author is that sensitivity analyses can be used only for identification and perhaps for ranking of uncertainty elements in terms of their importance and influence on model calculations and behaviour. This is also the view of Alcamo and Bartnicki (1985) who use sensitivity analyses for "screening and ranking" of model uncertainty elements. Essentially, uncertainty analysis covers a range of systematic methods for describing (often quantifying) and/or reducing uncertainty. There are many methods (approaches) that can be applied to model components, and provide some sort of quantitative estimate of the accuracy of the model results. The methods practically deal only with the technical uncertainties raised by model quantities such as parameters and/or variables. However, there are other methods, of the more "soft" type (see Rosenhead, 1989) which give a fairly good basis for handling uncertainties of a more structural and socio-political nature. They are, however, focused more on use in the whole decision-making process as outlined in the Two Level Planning Approach suggested in Sørensen (1994b). But there are cases where the methods have been applied in the process of developing models for decision support (see for example Olafsson and Wallace, 1993).

Going back to the technical uncertainties, there is no consensus or any standard on which methods to apply to the different uncertainty elements. Some methods are used more than others in the environmental modelling field. They can therefore be regarded as standard methods for uncertainty analysis of model uncertainty elements (environmentally related models). The methods have already been mentioned in connection with the evaluation of the RAINS model (Sørensen, 1994c). In Table 3.5, the methods are outlined in terms of their focus and the basic assumptions underlying their use.

It should be mentioned that several authors such as Fox (1982), Gass (1983), Morgan and Henrion (1990), Alcamo and Bartnicki (1985), Janssen *et al.* (1990)[1], Mobley (1992), Funtowitcz and Ravets (1990), and Rosenhead (1989) have pointed to methods applicable to models used in decision-making and the decision-making situation as such. The table also includes two examples of "soft" methods dealing with more structural uncertainties of both modelling and decision-making.

In general, the technical uncertainty methods tend to focus on the uncertainty which is expressed through the model output. This uncertainty can be imposed by varying factors. The first four methods are directly oriented towards uncertainty imposed by input quantities to the model calculations. The three last methods are focused on this aspect as well, but have a larger field of application where elements of the model structure, functional relations, model operations, constraints, etc. can be included.

The convergence intervals, Gaussian First Order, Monte Carlo simulation, and Latin Hypercube sampling can all be referred to as methods for handling uncertainty about values. Comparisons and scenarios can be described as methods for handling uncertainty about structure and relationships.

It will be seen that the assumptions underlying the use of the methods are most

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1. The publication is in Dutch which means that the author only knowns of the contents in overview. However, the publication has a comprehensive and useful reference list referring to the different methods reviewed.

Table 3.5. The uncertainty methods, their focus and assumptions behind.

Technical Uncertainty	Focus of Test	Common Assumptions
Convergence intervals[1]	Interval where the expected mean value of the model output lies with a certain probability	The variance of the model output is known, the model output is distributed as a normal distribution
Gaussian First Order[2]	Analytical expression of the variance of the model output	The inputs are non-correlated, there is a linear relationship between the inputs and the output, the variations of the inputs are known
Monte Carlo simulation[3]	The probability distribution of the model output	Each input is considered to be known with a known probability function, the input values are considered as independent
Latin Hypercube sampling[4]	The probability distribution of the model output	Each input is considered to be known with a known probability function, the input values are considered as independent
Comparisons	Establishment of visual uncertainty or a quantitatively estimate for the uncertainty imposed in the model output	That the model results have a comparable basis, objectivity of the involved parties
Scenarios	Visual uncertainty in the model output as a consequence of varying basis values or assumptions	That the uncertainty of the basis scenario is known or small
Structural Uncertainty	**Focus of Test**	**Common Assumptions**
The Strategic Choice Approach[5]	Handling of uncertainties so an incremental decision can be made	Cooperation of decision-makers and scientists, subjectivity and skill of the person who leads the process
Robustness Analysis[6]	Handling of uncertainty so an incremental decision can be made	Cooperation of decision-makers and scientists, subjectivity and skill of the person who leads the process, outcomes of actions can be predicted with relatively certainty

[1]See for example Morgan and Henrion (1990)
[2]See for example Morgan and Henrion (1990)
[3]See for example McKay *et al.* (1979)
[4]See for example McKay *et al.* (1979)
[5]Friend and Hickling (1987)
[6]Rosenhead (1990)

restrictive regarding methods for handling uncertainty about values. Some of the assumptions made regarding the input quantities are not necessarily valid. One example can be mentioned; the assumptions about independence of input variables/parameters and their variations.

When dealing with environmentally related systems, it is seldom that all the assumptions for using the methods are fulfilled. This is mainly because parameters, for example, are estimated or just set on the basis of subjective assessments. The quantities can rarely be measured or estimated accurately. In spite of this, the methods are applied anyway, assuming that the assumptions are fulfilled. This is of course one way of overcoming difficulties in giving uncertainty estimates, but simultaneously there is a risk of introducing uncertainty into the uncertainty analysis itself. The value of such an analysis can then be questioned.

The methods of assessing uncertainty about structure and relationships contain less strong assumptions and therefore have much larger application areas. On the other hand, they do not offer explicit uncertainty measures, but merely form the basis for more subjective assessments. The methods may, therefore, seem weaker than the methods of handling value uncertainty. This is not necessarily true, but it does play a psychological role when selecting or reading about the method and its results.

Considering the output of the uncertainty analyses, these must be said to be quite different. Figure 3.3 gives some examples of output from the above mentioned uncertainty analyses. There are, however, many other ways of expressing these results and the figure gives just a few examples, as it is commonly seen in publications. The examples are mainly given in terms of graphical presentations which is generally regarded as being the easiest way to quick understanding.

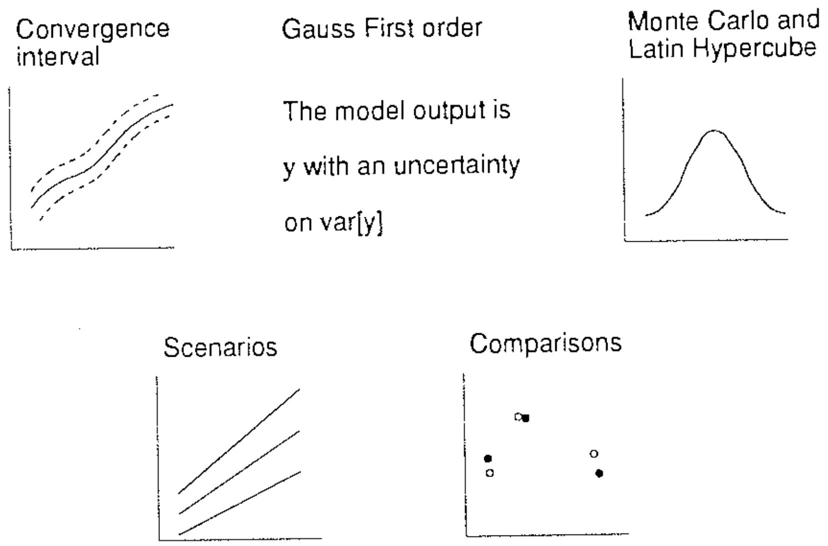

Figure 3.3. Examples on output from model uncertainty analyses.

From a user's point of view, the methods giving an explicit value of the uncertainty are the strongest and most useful. But they are also the most difficult to apply to models like Integrated Environmental Models.

As mentioned in Sørensen (1994c), there is no single uncertainty analysis that can be used for all parts of an Integrated Environmental Model. This was also a conclusion from investigating possible sensitivity methods for use with the RAINS model (see Sørensen (1994c). In general, the model must be treated in fragmented approaches where individual uncertainty elements in each submodel are addressed. It is very difficult to judge the uncertainty of the total model output, since the various uncertainty elements are propagated through the models' different components. To the author's knowledge there is no existing report on the use of one method for analyses of all uncertainties in an IEM. The stochastic methods (Monte Carlo and Latin Hypercube) are perhaps the most technical methods it has been attempted to use. But with the large structure of IEMs, it soon becomes a huge problem to perform calculations — the size of the computer program becomes enormous. Therefore, single uncertainty elements are selected, analyzed, reported in publications, and seldom built into the model itself.

The methods for handling structural uncertainty are of a different type, since they can only be used simultaneously with the process of decision-making. The author regards these methods as being positive and contributive in a decision-making process. The methods are seen applied in real world situations. The Strategic Choice Approach was last seen used in the development of a fisheries management model to be used on Iceland (see Olafsson and Wallace, 1993) where the principles of the method were successfully used in a collaboration between model developers and the legislative authority on Iceland. However, like the technical methods, the method has some limitations. It requires a high level of acceptance of the methods, willingness to use the method, and a high level of trust in the person/group facilitating and leading the process. The methods do not give an uncertainty estimate similar to the technical methods (as already mentioned) but offers instead to structure the problem in order to reduce the structural uncertainty.

As already mentioned, the technical methods presented above are just a small selection of an overwhelming variety of different methods for representing, propagating, analyzing, and handling uncertainties. Most methods have developed within different application areas, where it has become almost a tradition to use exactly this specific method. Most methods are therefore also reported in publications associated with these particular fields. There has been a more extensive application of different techniques to the same problems — but this is of a relatively new date. Naturally, the trend of developing and using Integrated Environmental Models in policy management makes this wider approach more relevant.

Comparing the methods, as for example outlined in this section, with the uncertainty elements identified in section 3.1, it is evident that the methods address only a fraction of the total number of uncertainty elements. The deficiency must lie with the traditions determining how uncertainty is accepted as an influential factor. As already mentioned, technical uncertainties are managed through uncertainty analyses and evaluations.

In order to take into account more uncertainty elements, it is necessary to widen the traditional concepts of uncertainty analyses and evaluation. A broadening of the concept of model evaluation has already been suggested in Sørensen (1994c) where the models' applicability in decision-making were judged on criteria such as robustness, accuracy, simplicity, transparency, adequacy, and effectiveness. Looking upon the whole planning and decision-making process this is not, however, sufficient for dealing with all uncertainties, including political ones.

Focusing on the processes of the case studies, and the uncertainty elements associated with decision-making as identified in section 3.1, it is clear that the decision-making processes as they are expected to evolve are unable to deal with the more structural and socio-political uncertainties of the processes. With the Action Plan process and partly the NEPP process in mind, it is evident that the uncertainties arising in these processes were influential on the processes. Furthermore, it is clear that the traditions of environmental decision-making do not offer any method for handling these uncertainties. Flexibility is introduced into the planning and decision-making in both the NEPP process and with the Two Level Planning Approach suggested in Sørensen (1994b). However, it is the view of the author that if all uncertainty elements of Table 3.3 are present, these aspects are not necessarily sufficient to control the decision-making processes. No methodological approach can deal with all uncertainty elements.

With the conclusion on the roles of scientific/models in environmental planning and decision-making in mind (from Chapter 2), it is evident that some consideration must be paid to how the model is used. The Action Plan process was heavily influenced by uncertainties (as concluded in Sørensen, 1994b) while it seems that the processes of the NEPP and RAINS were not influenced (the NEPP process was of course influenced by uncertainty in the last phase of adoption of the plan — but as concluded: not all uncertainties can be handled or controlled). Therefore there must be a close relationship between the planning and decision-making processes as they take place within the constitutional settings and between the actors involved, and the uncertainties that may affect the process and its outcome. Consequently, attention must be paid to the development of the process and the problems dealt with. *Social model assessment* can be a suggestion for an extended evaluation. The term is borrowed from Vidal (1992). In this analysis, the socio-economic and political process behind the solving of the environmental problem should be investigated, along with the political and social consequences of using mathematical models in the process. Furthermore, it should be tried to seek out the aims and practices of modellers/scientists in order to identify their roles in the process. The structural and socio-political uncertainties associated with the policy uncertainty elements can only be dealt with methodologically through such overall sociological analysis.

3.3 Summary

In the case studies, uncertainty was identified as a factor influencing the evolvement of problem-solving processes.

Uncertainty elements, i.e, the points from where uncertainty can arise in the problem-solving process, are identified and classified in a model uncertainty taxonomy and in a policy uncertainty taxonomy. The various classes of uncertainty elements may raise uncertainty of different types.

Model evaluation is the concept within which model uncertainties are addressed in traditional terms.

There are several methods for managing uncertainty, or more specifically the uncertainty elements. However, most methods address the technical uncertainties associated with quantification of model uncertainty elements. Other uncertainty elements are not dealt with. This fact can mainly be attributed to the difficulties in managing the uncertainties. Existing methods of dealing with uncertainty can only be used with the Integrated Environmental Models in fragmented approaches, leaving behind questions about the uncertainty of the whole model and how the single uncertainties are propagated through the model calculations.

Therefore, there is a general need for model evaluations where the applicability of models in real-world decision-making is judged from specific criteria. In order to deal with the more structural and socio-political uncertainties, it is necessary to perform more fundamental model and social assessments, where sociological considerations are applied to the social system performing environmental decisions, to the problem itself, and to why the models as such are needed in this process.

4 Conclusion

In the three parts of the present thesis environmental planning has been analyzed in terms of how mathematical models are used in planning and in terms of identifying uncertainties influencing the planning process. The work has basically been carried out by analyzing three real-world examples of environmental planning and decision-making.

The thesis shows that scientific information and especially mathematical models (such as Integrated Environmental Models) are used in environmental planning. Analyses of the case studies show that the mathematical models can be used in many different ways and roles in planning and decision-making. Each of the three case studies illustrates one variant of a planning and decision-making process and one way of using mathematical models. The models can be used for the purposes of justifying political decisions, supporting decisions, and steering or almost controlling the space of options for solving a specific problem.

The case studies illustrate that the use of models in real life planning is associated with some limitations. The models do not necessarily apply well to the problem or to the environment in which they shall be used. In spite of this, they are used anyway. One conclusion is that the use of models is highly dependent on the constitutional framework for solving the problems, i.e., the national and international systems, and the actors participating in the process.

Uncertainty is a factor influencing environmental planning and decision-making. Uncertainty in environmental planning occurs in at least three types, of which the thesis has identified the technical, structural, and socio-political types as the most important. A large number of uncertainty elements can be identified, associated both with the mathematical models and with the policy making environments of planning. The elements are identified directly in the case studies and are classified into a model taxonomy where the most evident uncertainty elements are outlined.

Studying methods of handling and describing the uncertainty elements, it is clear that only a small fraction of the elements can be handled by means of traditional mathematical methods. Most existing methods address only technical model uncertainties. Furthermore, these methods are difficult to apply to the Integrated Environmental Models, and to the planning and decision-making process as such. Structural and socio-political uncertainties within the process require a wider ranged approach. The thesis suggests that consideration should be given to the wider perspectives of handling uncertainties. A model evaluation concept is suggested, where not only specific technical uncertainties are analyzed, but also more general conditions in order to judge the models' applicability in planning and decision-making. Other types of uncertainty require more fundamental social analyses in order to find methods for handling and dealing with them.

The fundamental hypotheses underlying the work must therefore be said to have been verified.

The work presented in the thesis can be continued on several fronts.

The study has been carried out by an author with technical background. During the work it has, however, become evident that to reach a full conclusion on the role and limitations of models in environmental planning, a more sociologically oriented analysis is required.

In connection with the handling of model uncertainty, there is an obvious need for updating the concepts associated with uncertainty analysis, evaluation, etc., in order to make them more relevant to models used as decision-support — like the Integrated Environmental Models. The thesis has only suggested a change of one concept, but there are many more needing adjustment. Furthermore, the author believes, that because models are used in planning, it is necessary to find and/or establish some sort of consensus on the methods (referred to as methods of uncertainty analyses in the thesis) that can be easily applied to models of this type, and understood by non-mathematical experts. Only through analyses and explicit explanations of the models' assumptions, behaviour, etc., can the models be documented, and the limitations on their use become visible. This may give results in showing the value of the models, but also in showing the problems and situations in which the models should not be applied.

Uncertainty is one of many factors that can influence environmental planning. It can never be totally avoided or controlled, but much can be gained through explicit discussions. It is hoped that this thesis has contributed to these discussions.

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A Annex 1: The Concept of Integrated Environmental Models

The Integrated Environmental Model is a broad, not particularly well-defined concept. As already described in Chapter 3, it posseses the following characteristics as outlined in Figure A1.

The model type is considered to be grouped under Decision Support Systems (DSS) (see for example Guariso and Werthner(1989), Vidal (1990), or Fedra and Reitsma (1990)) where the overall aim of the model is to support decision-makers in making important decisions.

Integrated Environmental Models:

Addresses environmentally related issues

DSS-characteristics

- Provide scientific support to decision-makers
- A certain level of flexibility for interactive model use (mostly in terms of user defined scenarios)
- Includes a dialogue system for graphical presentation of model results

Module-characteristics

- Interdisciplinary Perspectives covered by different modules
- The modules include inter- and intradisciplinary relationships
- The timely perspective considered is long-term influences
- The spatial perspective considered is regional or global scales

Figure A.1. Characteristics of Integrated Environmental Models (based on Brouwer (1987) and Braat and van Lierop (1987)).

Integrated Environmental Models are developed through a multidisciplinary approach by environmentally relevant disciplines. As examples of interdisciplinary perspectives can be mentioned; national change or development of the environmental system; man's influence on the system as resource exploitation, impacts of, e.g., consumption activities; natural processes (biological, chemical, physical); socio-economic relations between for example disposal of waste or byproducts of consumption activities, energy use, and economic interests. The environmental system is the central issue in the model, but aspects relating closely to the description of the system are also represented by submodels or modules. Nothing is assumed about the type of modules in terms of mathematical relations used — these can vary as much as wanted. However, it is assumed that at least two of the modules (or submodels) address the system from viewpoints of different fields of science. An example is the RAINS model (see Sørensen, 1994c) which includes modules focusing on the energy system, on meteorological issues, on ecological impacts, and on the economics of different strategies for solving the acidification problem in Europe.

As implied in the name Integrated Environmental Models, the modules comprising the model must be linked by variables not only within the single modules themselves (intradisciplinary relationships), but also by variables in other modules crossing the boundaries of the single modules (interdisciplinary perspectives). Intradisciplinary perspectives are usually linked by functional relations, while the interdisciplinary perspectives can be of varying character. As an example of interdisciplinary perspectives can be mentioned a variable used without transformation for calculations in another module. However, sometimes the linkages need a transformation of some type (see again the RAINS model where transformations from the Energy/Emissions/Costs module are linked to the Critical Loads Assessment Module by a linear relationship between emissions and depositions and a source-receptor matrix. Sørensen, 1994c).

Due to the environmental problems of today, the Integrated Models are characterized by their long-term perspective and a spatial coverage that must be said to be of regional[2] or global character. This constraint is put into the characterization because of the possible use of the models in practical environmental policy making and management.

The Structure

In general the Integrated Environmental Models are developed through a systems analysis approach where the characteristics of the phenomena themselves are considered to be as important as their interactions and feedback relationships. In principle there are many ways of developing Integrated Models, i.e., organizing and linking the modules. Brouwer (1987) and Hafkamp (1984) mention four fundamental principles:

The horizontal model approach where the relevant modules are considered to be equally important in contributing to the model's conceptualization and operation. Additionally, the different modules are considered with equal levels of detail in the spatial and time coverage.

The vertical model approach where one or more modules are considered superior to the others. In this approach special emphasis is put on describing the relationship between the dominant module/modules and the other modules. The level of detail considered in the various modules may vary.

The satellite design approach is a combination of the horizontal and vertical approaches. One module is considered as the central core of the model and the centre of the analysis. All important model components are gathered in the core module while at the same time being linked to, or represented in, all other modules in the model. All components not represented in the core module are linked to each other. Again, the level of detail may vary between the modules.

The multilayer approach can be represented by each of the above mentioned approaches. The distinction is that more layers represent the same set of sub-systems, but the disciplines by which the sub-systems are modelled vary amongst the layers.

In Brouwer (1987), Braat and van Lierop (1987), and Hafkamp (1984) an overview of different Integrated Environmental Models can be found. They will not be reviewed here.

However, not all model structures fall into these categories. One example is the

2. Regional is used in broad terms relating to an area or system that can be characterized as non-homogeneous in respect to the issue in focus.

RAINS model (see Sørensen, 1994c) which can be seen in a schematic overview in Figure A.2. The overview is given in terms of module/sub-models structure, linkages, and detail level considered. A more thorough description can be found in Sørensen (1994c).

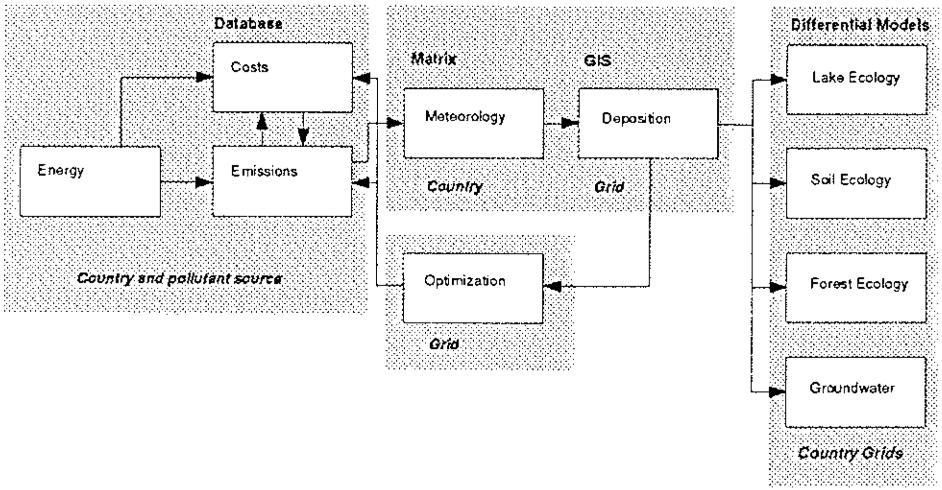

Figure A.2. The different modules and sub-models' types and level of detail in the RAINS model.

Integrating information from several scientific, technical and social sciences into one model, needs a somewhat different modelling approach than in the case of models developed from a mono-disciplinary viewpoint as illustrated in Figure A.2. A commonly used approach for constructing IEMs is to link together several mono-disciplinary submodels or compartments where the different submodels describe various aspects of the problem in focus. In RAINS, energy, economic, meteorologic, and ecologic aspects are considered. Due to different traditions of mathematical approach in different fields of science, and the issue in focus (some submodels can be considered as more important than others), the IEM can include submodels which are highly different. Differences can exist in mathematical structure, spatial and time perspective, level of detail in the description (aggregation level) and need for quality and quantity of data. See again Figure A.2 where a database, Geographical Information System (see Fedra and Reitma, 1990), differential models, and optimization models are combined, and where the aggregation level of the modules/sub-models vary between country, source, and grid cells. It may therefore be necessary to transform or adapt information to be exchanged between submodels e.g. through changes in the model structure of one or several submodels, or to specify/define new variables and relations. Depending on how the submodels are linked, some submodels can form a small individual part of the IEM structure which can work independently of the other submodels. In RAINS some of the modules can be worked independently of each other (the Database module, and the matrix/ GIS module), although some input from other modules is necessary.

An integrated model can be intended for use as a simulation model (where the main purpose is prediction), as an optimization model, or as a combination of both. Existing models are almost equally divided into these 3 categories (Braat and van Lierop, (1987). RAINS is an example of a model employed for a combination of simulation and optimization purposes.

Further details on the construction and structure of the IEMs can be found in, e.g., Brouwer (1987), in Braat and van Lierop (1987), and in Hafkamp (1984).

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Lene Sørensen

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The purpose of the project has been to analyze environmental planning processes, the application of scientific information in the form of mathematical models, as well as the identification of significant factors that can give raise to uncertainty and affect the structure and outcome of planning processes.

Three different examples of environmental planning are presented, compared and analyzed. Uncertainty has been identified in the case studies as a central factor in planning. Three types of uncertainty is found; technical, structural, and socio-political uncertainty. The project suggests a way of classifying the uncertainties present in order to be able to cope with these.

The report represents the first part of the Ph.D. thesis on Environmental Planning and Uncertainty.

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